US006707429B1

(12) **United States Patent**
Siegel

(10) **Patent No.: US 6,707,429 B1**
(45) **Date of Patent: Mar. 16, 2004**

(54) **SELF-CONTAINED SUB-MILLIMETER WAVE RECTIFYING ANTENNA INTEGRATED CIRCUIT**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/318,670**

(22) Filed: **Dec. 9, 2002**

(51) **Int. Cl.**[7] **H01Q 1/12**

(52) **U.S. Cl.** .... **343/700 MS**; 343/770; 343/795

(58) **Field of Search** .... 343/700 MS, 767, 343/770, 795, 829, 846; 437/203, 906; H01Q 1/12

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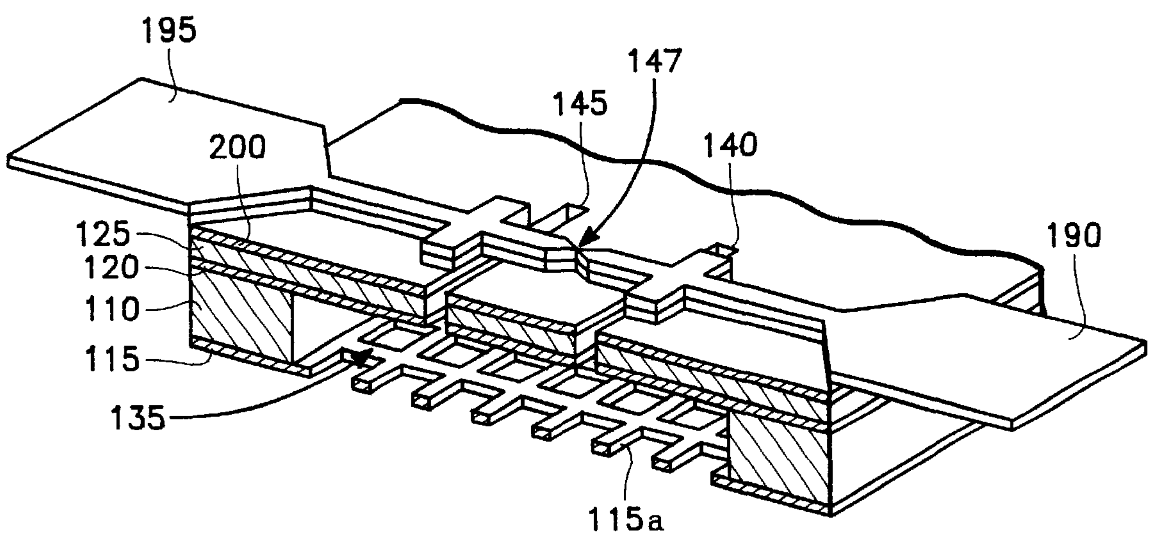
(57) **ABSTRACT**

The invention is embodied in a monolithic semiconductor integrated circuit in which is formed an antenna, such as a slot dipole antenna, connected across a rectifying diode. In the preferred embodiment, the antenna is tuned to received an electromagnetic wave of about 2500 GHz so that the device is on the order of a wavelength in size, or about 200 microns across and 30 microns thick. This size is ideal for mounting on a microdevice such as a microrobot for example. The antenna is endowed with high gain in the direction of the incident radiation by providing a quarter-wavelength (30 microns) thick resonant cavity below the antenna, the cavity being formed as part of the monolithic integrated circuit. Preferably, the integrated circuit consists of a thin gallium arsenide membrane overlying the resonant cavity and supporting an epitaxial Gallium Arsenide semiconductor layer. The rectifying diode is a Schottky diode formed in the GaAs semiconductor layer and having an area that is a very small fraction of the wavelength of the 2500 GHz incident radiation. The cavity provides high forward gain in the antenna and isolation from surrounding structure.

37 Claims, 8 Drawing Sheets



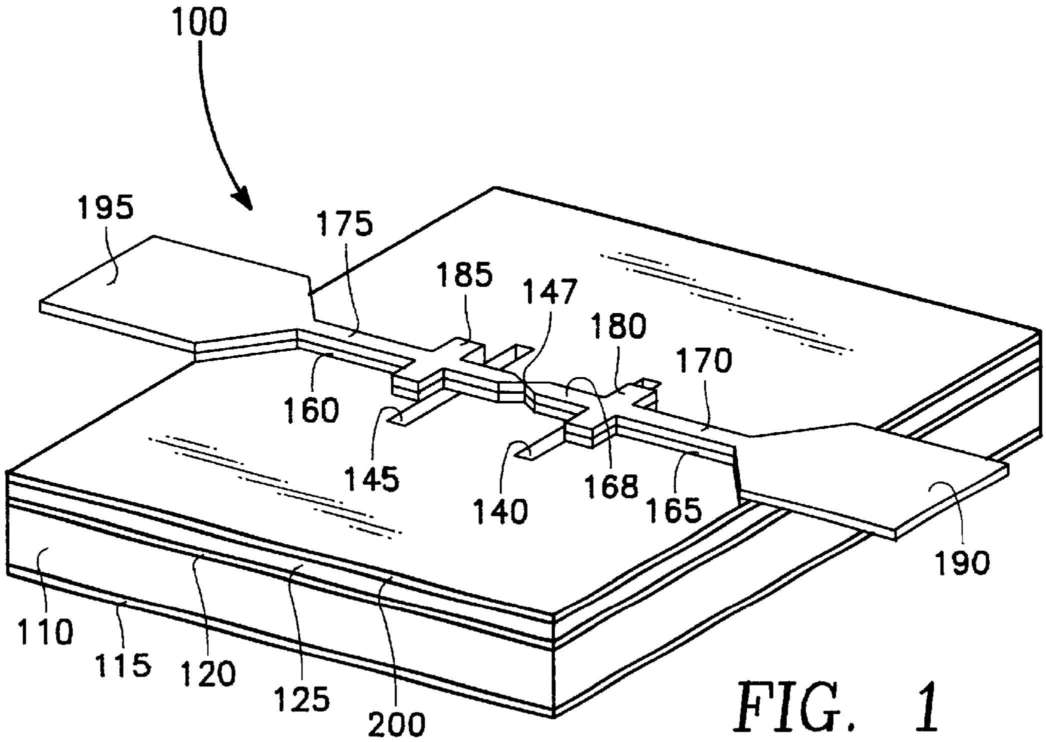

100
195
175
185
147
180
170
160
145
140
168
165
190
110
115
120
125
200

FIG. 1

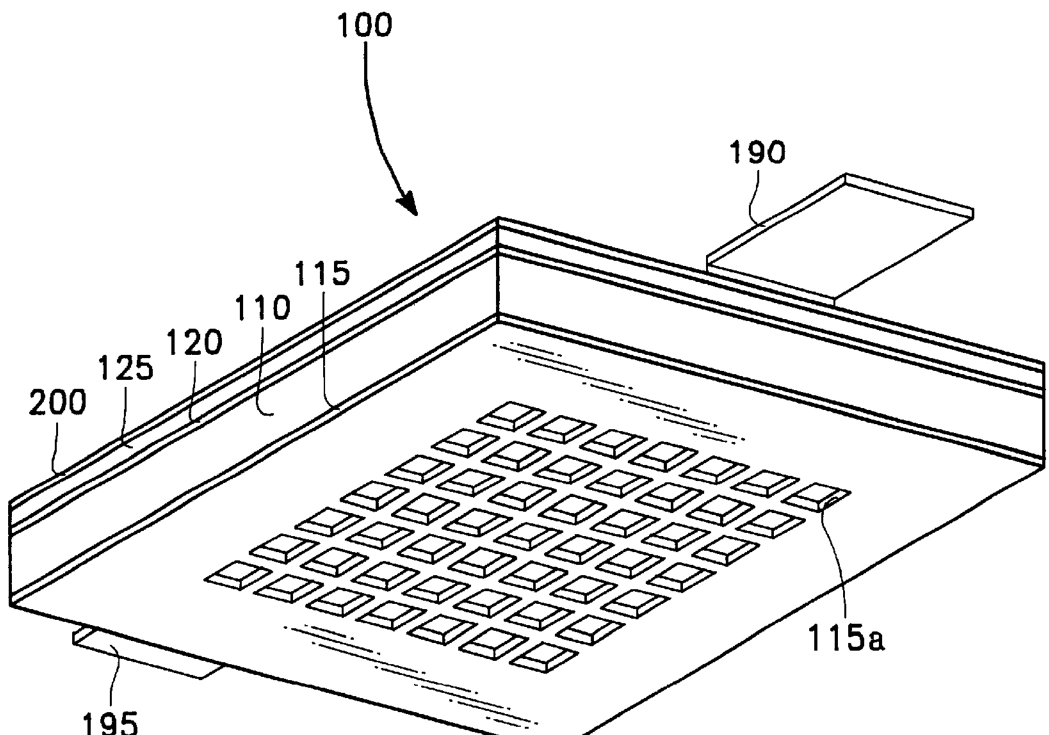

100
190
115
110
120
125
200
115a
195

FIG. 2

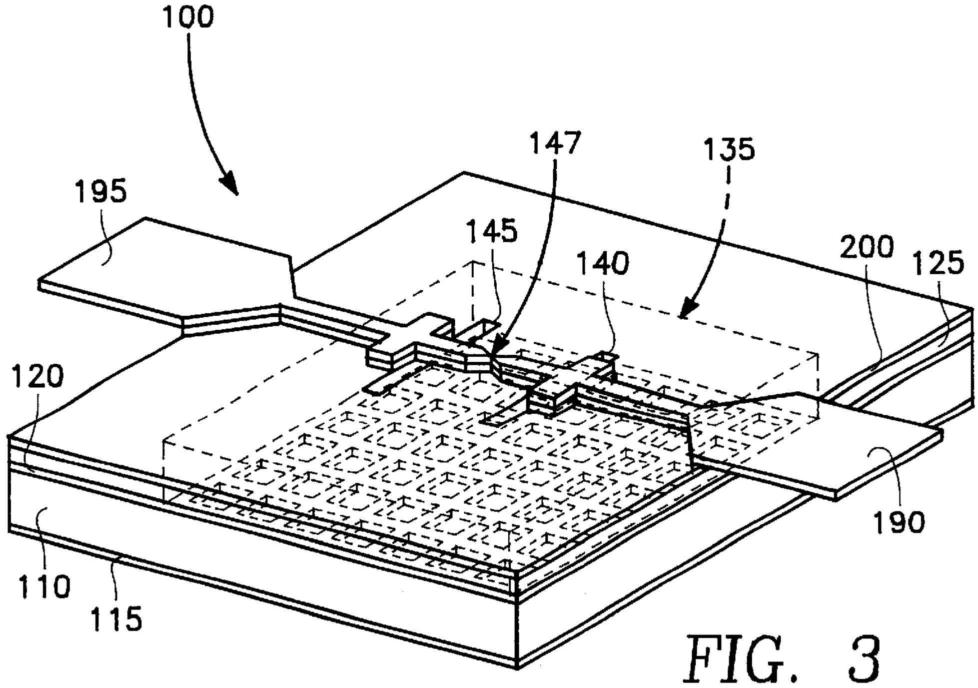

100
147
135
195
145
140
200
125
120
190
110
115

FIG. 3

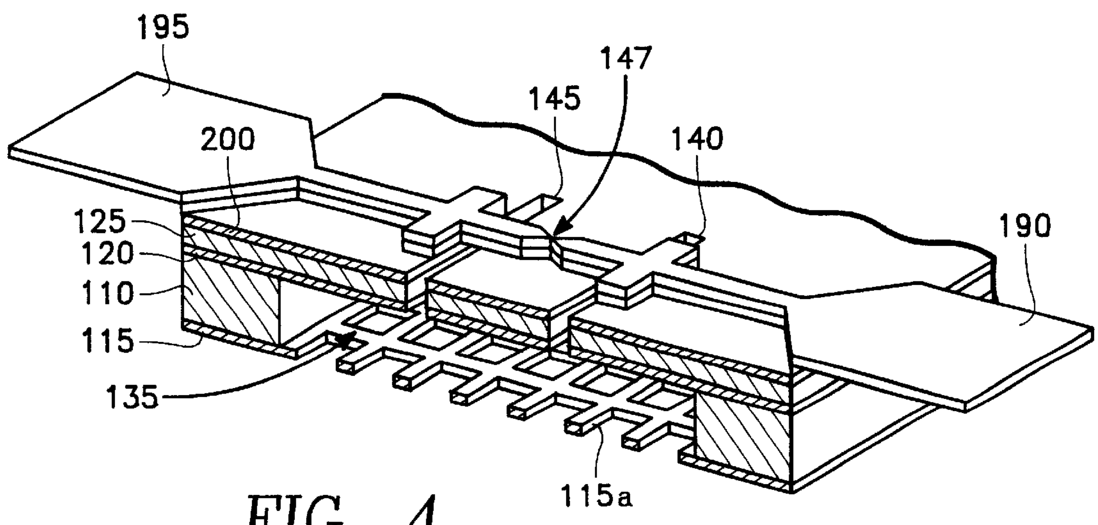

195
147
145
200
140
190
125
120
110
115
135
115a

FIG. 4

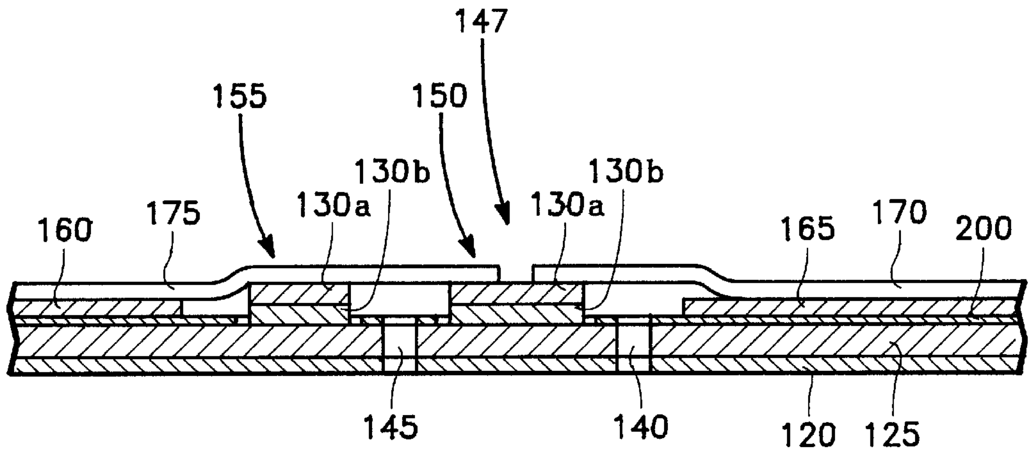

147
155
150
130b
130b
130a
130a
160
175
165
170
200
145
140
120
125

FIG. 5

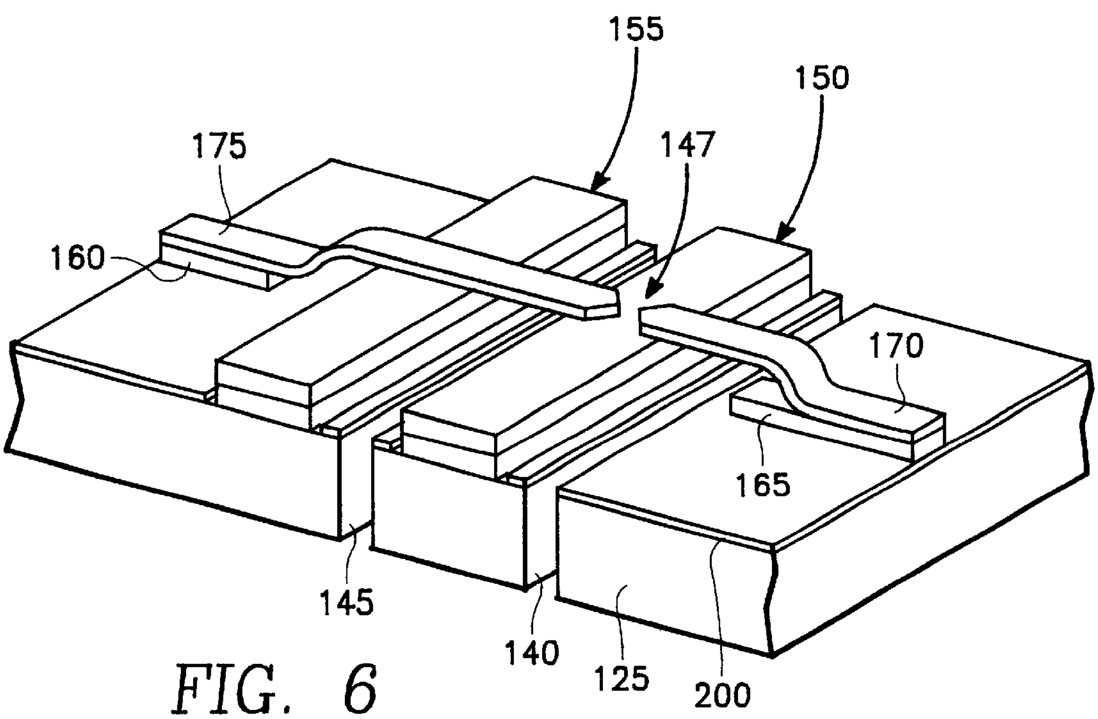

155
150
175
147
160
170
165
145
140
125
200

FIG. 6

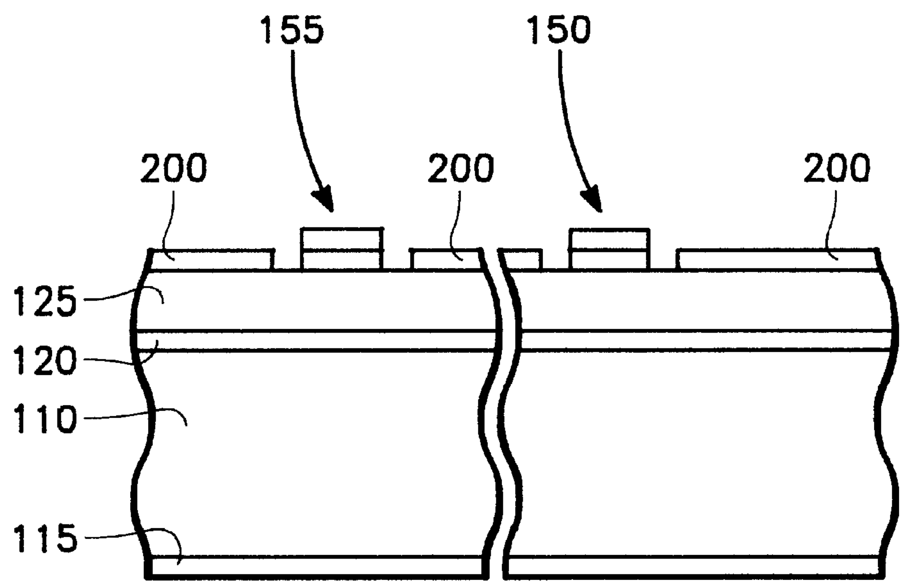

155
150
200
200
200
125
120
110
115

FIG. 7

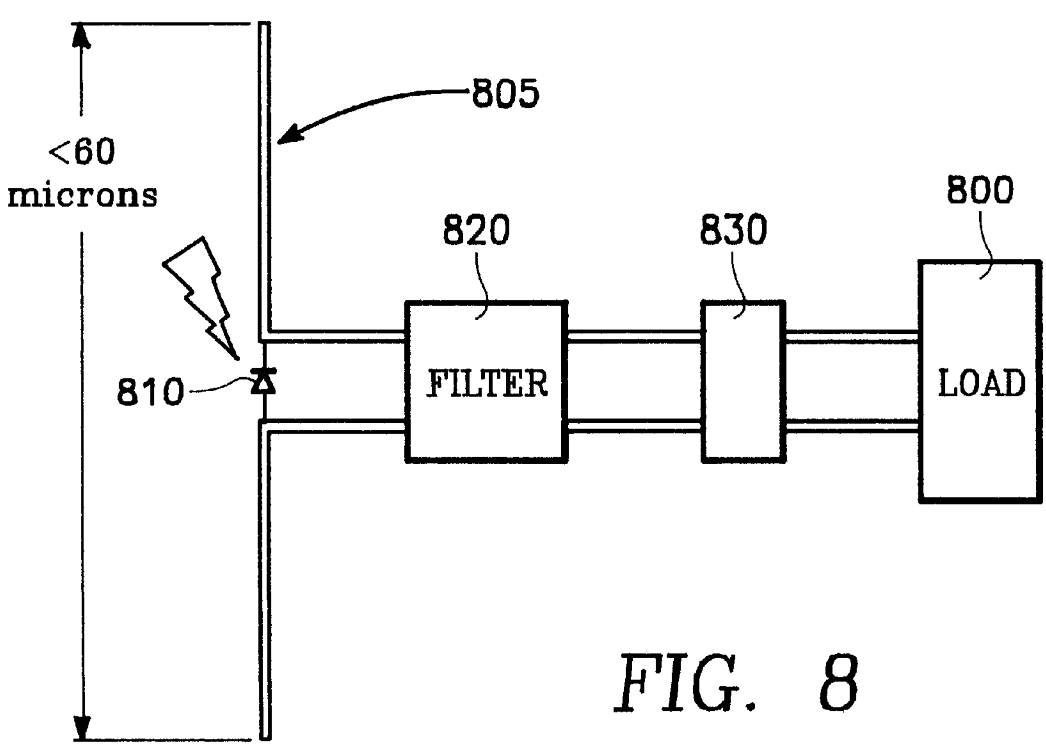

<60
microns
805
800
820
830
810
FILTER
LOAD

FIG. 8

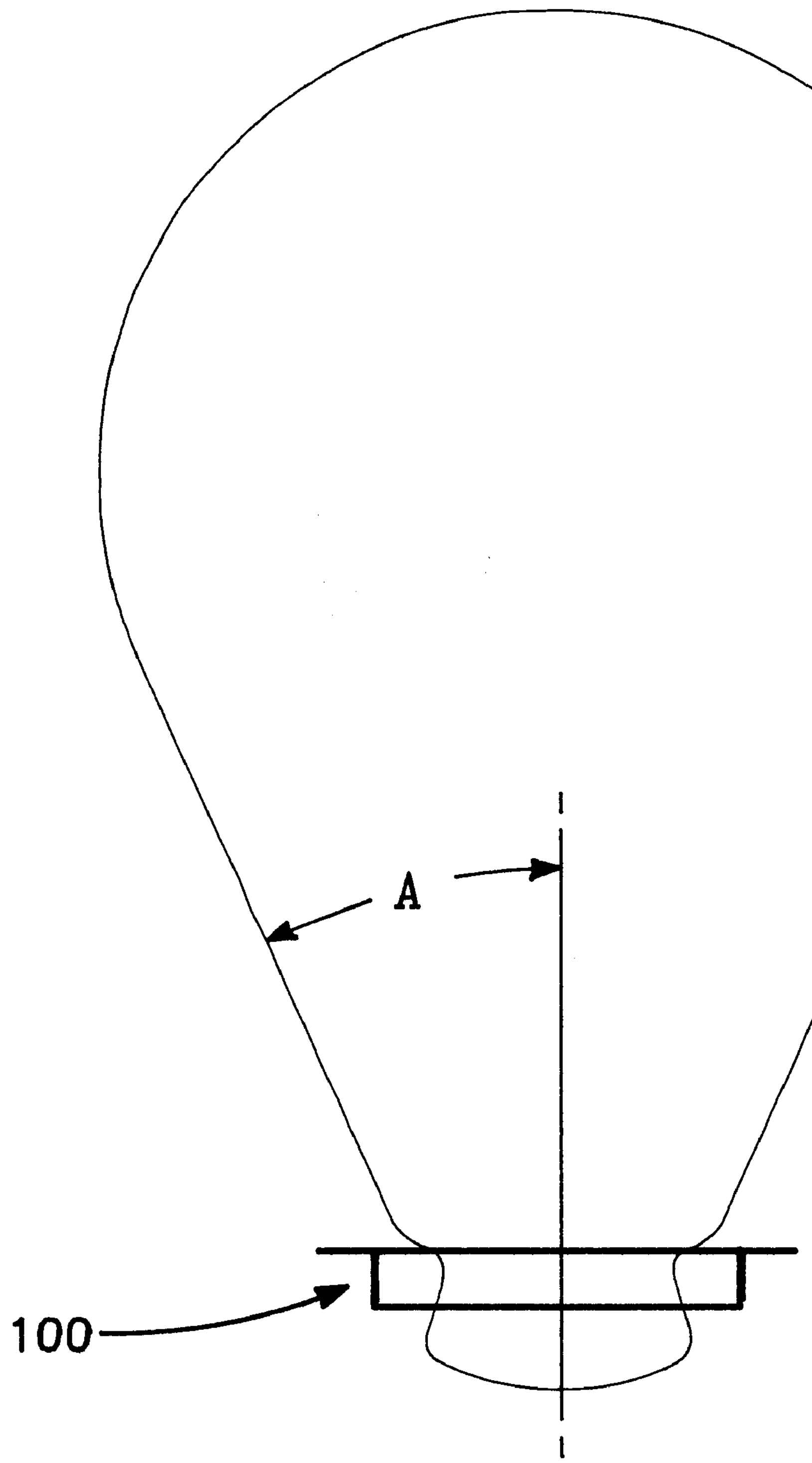


FIG. 9

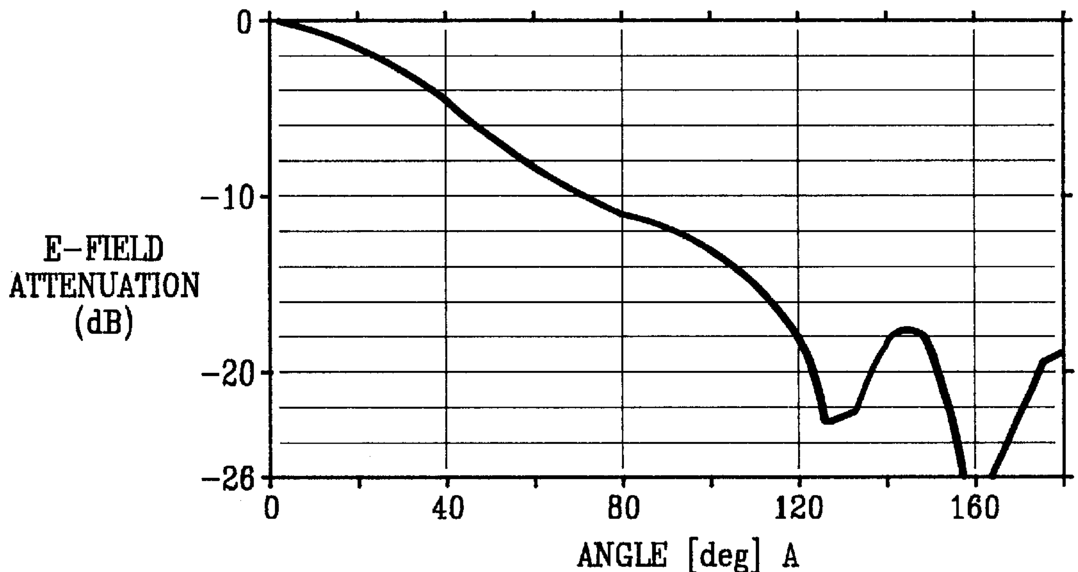

0
-10
-20
-26
E-FIELD
ATTENUATION
(dB)
0
40
80
120
160
ANGLE [deg] A

FIG. 10

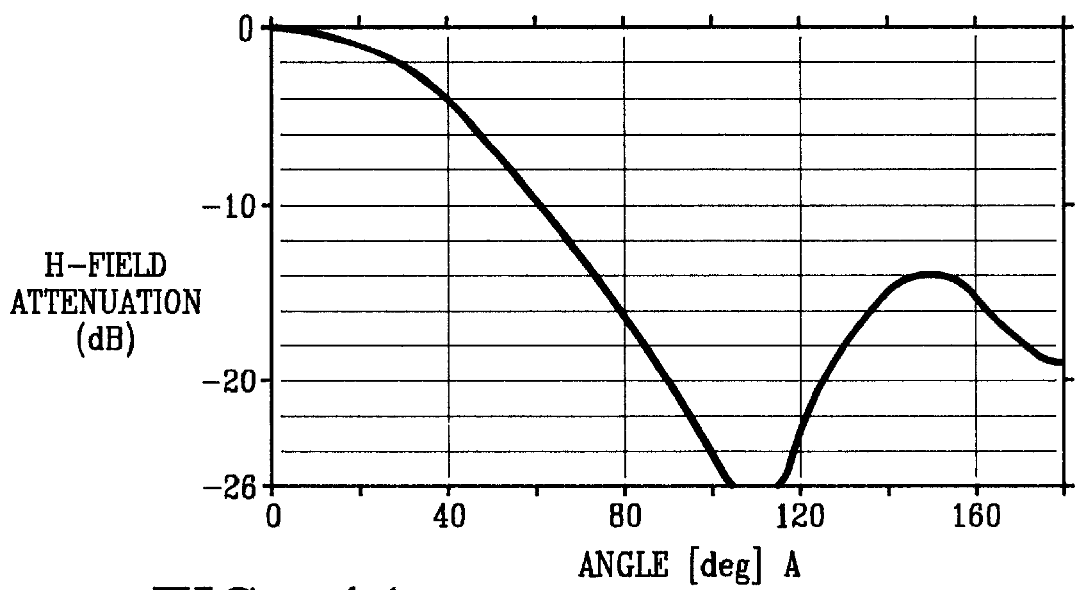

0
-10
-20
-26
H-FIELD
ATTENUATION
(dB)
0
40
80
120
160
ANGLE [deg] A

FIG. 11

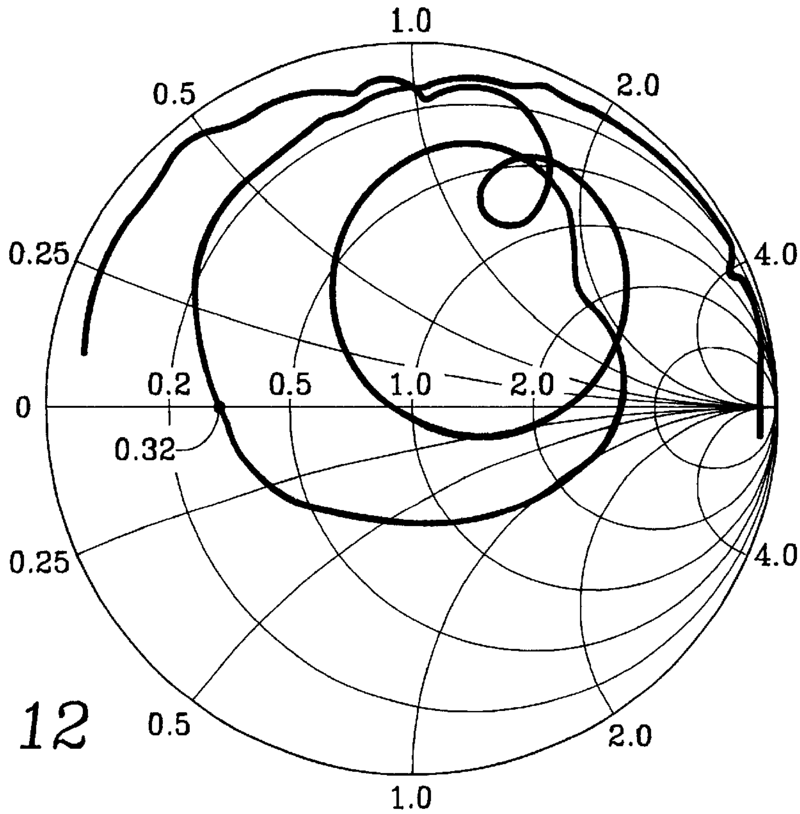


FIG. 12

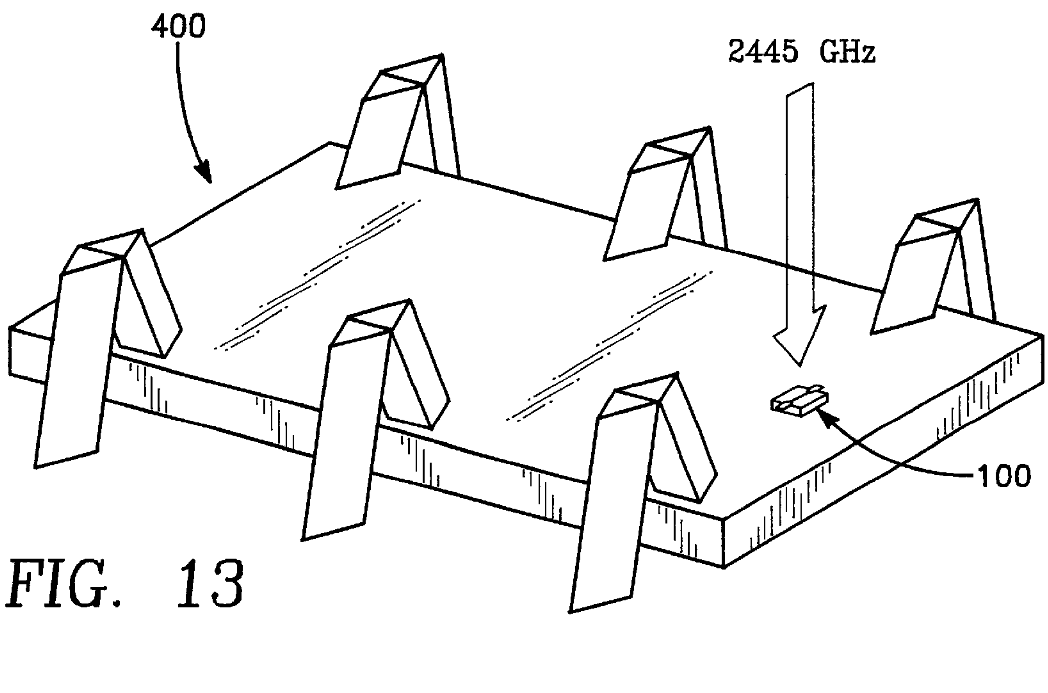
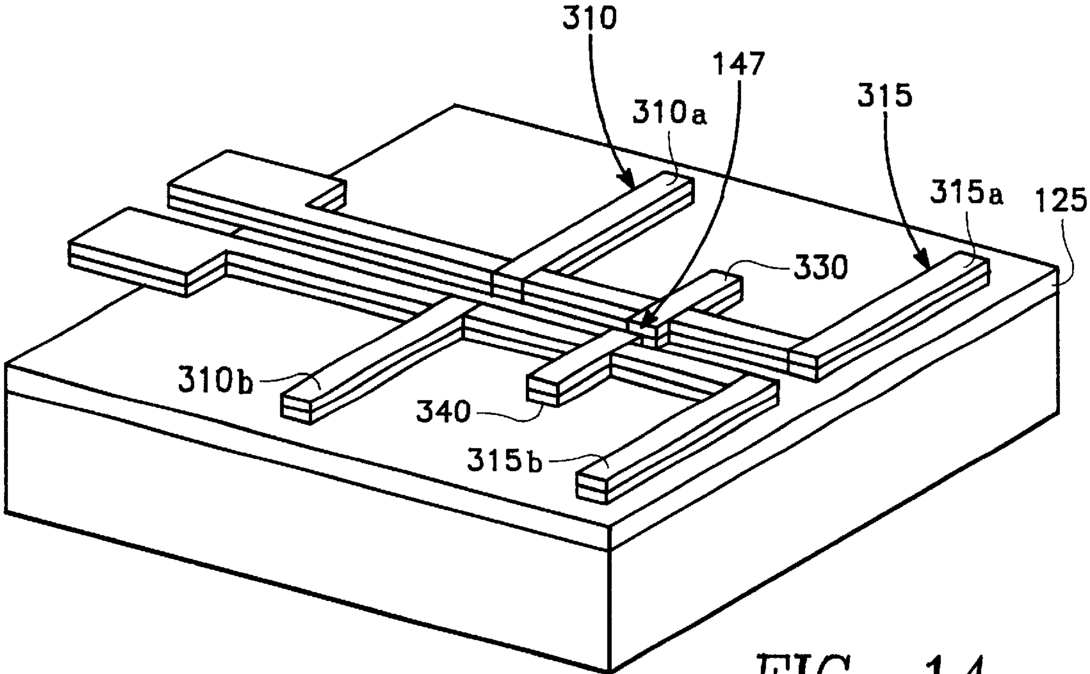
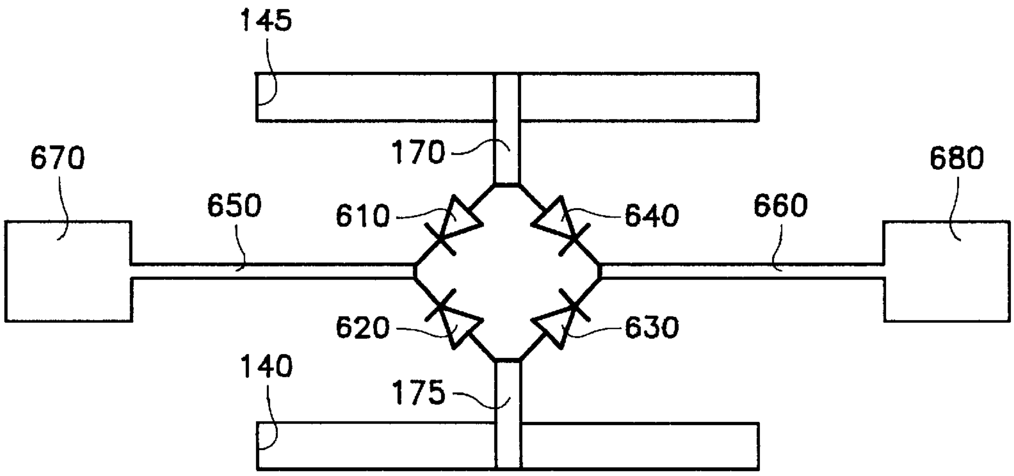


FIG. 13



310
147
310a
315
315a
125
330
310b
340
315b

FIG. 14



145
670
170
680
650
610
640
660
620
630
140
175

FIG. 15

SELF-CONTAINED SUB-MILLIMETER WAVE RECTIFYING ANTENNA INTEGRATED CIRCUIT

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. §202) in which the Contractor has elected not to retain title.

BACKGROUND OF THE INVENTION

The invention is related to power supplies for deployable Microsystems such as TeraHertz sensors, bioengineering nanodevices, micro-robots, nanofabrication and planar antennas. Supplying electrical power to micro-devices from a battery or from wires is often impractical because the weight of the wires or battery may impair the performance of the microdevice being powered. The present invention provides electrical power from electromagnetic radiation incident on a local antenna mounted on the microdevice to be powered. One problem with such an arrangement is that the antenna performance is affected by the electrical characteristics of the microdevice on which it is mounted. Thus, the design of the underlying microdevice is constrained so as to avoid detracting greatly from antenna performance, which is inconvenient. Another problem is that an antenna sufficiently small to fit on a microdevice, such as a microminiature dipole antenna, will typically have poor gain in the direction of the radiation because such an antenna will have little directionality. A further problem is that a diode must be employed to rectify the received RF power. The impedance of the diode will not necessarily match the impedance of the antenna, depending upon the frequency of the incident radiation, so that some power will be lost. Yet another problem is to find a radiation frequency at which the ideal antenna size is small compared to the microdevice on which it is to be mounted, but not so small that the frequency reaches the optical range in which a diode rather than an antenna must be used. This would sacrifice the advantage of tunability of an antenna. Further, it would be desirable if the radiation frequency were one that readily penetrated certain materials such as plastic, human skin (for bio-engineering applications) and the like.

SUMMARY OF THE DISCLOSURE

The invention is embodied in a monolithic semiconductor integrated circuit in which is formed an antenna, such as a slot dipole antenna, connected across a rectifying diode. In the preferred embodiment, the antenna is tuned to received an electromagnetic wave of about 2500 GHz so that the device is on the order of a wavelength in size, or about 200 microns across and 30 microns thick. This size is ideal for mounting on a microdevice such as a microrobot for example. The antenna is endowed with high gain in the direction of the incident radiation by providing a quarter-wavelength (30 microns) thick resonant cavity below the antenna, the cavity being formed as part of the monolithic integrated circuit. Preferably, the integrated circuit consists of a thin silicon membrane overlying the resonant cavity and supporting an epitaxial Gallium Arsenide semiconductor layer. The rectifying diode is a Schottky diode formed in the GaAs semiconductor layer and having an area that is a very small fraction of the wavelength of the 2500 GHz incident radiation. Preferably, the antenna is a pair of half-wavelength dipole slots in the overlying conductor layer that forms respective power output terminals and respective tuning capacitors across the rectifying diode. At the 2500 GHz frequency, the pair of half-wavelength dipoles exhibit an impedance that nearly matches the impedance of the Schottky rectifying diode, a significant advantage. A most significant advantage is provided by the combination in the integrated circuit of the antenna with the quarter wavelength resonant cavity, because the antenna behavior is determined principally by the resonant cavity. The resonant cavity both provides the directional gain of the antenna and isolates the antenna from surrounding structure. In this way, the integrated circuit may be mounted on any structure without appreciably affecting the antenna behavior.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a top perspective view of an integrated circuit embodying the present invention.

FIG. **2** is a bottom perspective view of the integrated circuit of FIG. **1**.

FIG. **3** is a transparent view corresponding to FIG. **1**.

FIG. **4** is a partially cut-away perspective view corresponding to FIG. **3**.

FIG. **5** is an enlarged cross-sectional side view of a portion of the integrated circuit of FIG. **1** showing the structure of a Schottky diode therein.

FIG. **6** is an enlarged perspective view of the Schottky diode of FIG. **5**.

FIG. **7** is an enlargement of portions of FIG. **6** showing in greater detail the semiconductor structure.

FIG. **8** is an electrical block diagram of an equivalent circuit corresponding to the apparatus of FIG. **1**.

FIG. **9** is a diagram illustrating a side view of a 3-dimensional antenna power distribution pattern of the antenna of the apparatus of FIG. **1**.

FIG. **10** is a graph showing the predicted electric field angular distribution of the antenna of the apparatus of FIG. **1**.

FIG. **11** is a graph showing the predicted magnetic field angular distribution of the antenna of the apparatus of FIG. **1**.

FIG. **12** is a Smith chart of the antenna of the apparatus of FIG. **1**, showing the occurrence of a nearly purely resistive impedance of the antenna at a selected frequency (2445 GHz) that nearly matches the impedance of the Schottky diode at the same frequency.

FIG. **13** illustrates the mounting of the apparatus of FIG. **1** on a known microrobot.

FIG. **14** illustrates how the slot antenna of FIG. **1** may be replaced by an equivalent conductor antenna.

FIG. **15** illustrates a modification of the embodiment of FIG. **1** in which the single rectifying diode is replaced by a full-wave diode rectifying bridge.

DETAILED DESCRIPTION

Referring now to FIGS. **1**, **2**, **3** and **4**, an integrated circuit **100** converts incident submillimeter wave radiation of a selected frequency to D.C. power. The integrated circuit **100** consists of a thin base layer **110** formed from a wafer such as a silicon wafer. The thickness of the base layer **110** may be about one quarter wavelength of the incident radiation, or about 30 micrometers (microns) if the submillimeter wave radiation frequency is 2500 GHz. Such a 30 micron base layer **110** may be formed by chemical mechanical polishing of a conventional silicon wafer to the desired thickness, for example. A metallic thin film layer such as gold **115** is

formed on the bottom face of the base layer **110** and an etch stop layer **120** is formed on the top face of the base layer. The composition of the etch stop layer **120** depends upon the etchant employed to etch the base layer **110** as will be described below, and may be, for example, silicon nitride. A thin membrane **125** is formed over the etch stop layer **120**, the membrane **125** being about 2 or 3 microns thick and being of either silicon or gallium arsenide.

A first etchant that is selective to gold is employed to etch a mesh pattern in the bottom gold layer **115** consisting of an array of small openings **115***a*. The length and width of each of small openings may be about one tenth of the incident radiation wavelength, or about 12 microns. A second etchant selective to silicon is employed to flow through the openings **115***a* and etch out the interior of the silicon base layer **110** to form a hollow rectangular cavity **135** inside the base layer **110**, the cavity **135** being shown in FIGS. **3** and **4**. The cavity **135** may be slightly in excess of one wavelength in length and width, or about 140 microns. The etch stop layer **120** fixes the depth of this etch step, and thereby determines the depth of the cavity **135**. Preferably, this depth is about a quarter wavelength, or about 30 microns.

A slot antenna structure is formed by etching a pair of parallel slots **140**, **145** through the gold layer **200** and through the silicon membrane **125**. The slots **140**, **145** are each about a half wavelength in length and their center-to-center spacing is also about a half wavelength, or about 60 microns for a 2500 GHz radiation frequency. They are each about 8 microns in width.

FIGS. **1–4** indicate a Schottky diode generally at **147**, the structure of this diode being too small for convenient illustration in these figures. The structure of the Schottky diode **147** is illustrated in detail in the exploded views of FIGS. **5–7**. In order to form the diode **147**, a very small window (too small to be seen in FIGS. **1–4** but visible in FIGS. **5–7**)) is formed in the gold layer **200** in the region of the diode **147** in order to expose the top surface of the mesa **125** in this small region. A gallium arsenide (GaAs) active semiconductor layer **130** is formed over the small portion of the membrane **125** that has been thus exposed. Preferably, the GaAs layer consists of a bottom highly doped n-type (n+) layer **130***b* and a top lightly doped n-type (n) layer **130***a*. Referring to FIGS. **5**, **6** and **7**, the GaAs layer **130** is etched to form a GaAs mesa **150** and, if desired, an optional second GaAs mesa **155**.

An insulating (e.g. silicon dioxide) layer is formed over the entire structure and then etched to define elongate insulating mesas **160**, **165**. A conductor (gold) layer is deposited and then etched to define a first elongate conductor **175** on the elongate insulating mesa **160** and bridging between the insulating mesa **160**, the GaAs mesa **155** and the GaAs mesa **150**, and a second elongate conductor **170** on the other elongate insulating mesa **165** bridging between the insulating mesa **165** and the GaAs mesa **150**. The elongate gold conductors **170**, **175** and the underlying elongate insulating mesas **160**, **165** are generally congruent so that the gold conductors **170**, **175** are everywhere insulated from the underlying gold layer **200**. The Schottky diode **147** is formed at the contacts made by the two conductors **170**, **175** to the top surface of the GaAs mesa **150**.

The overall configuration of the two conductors **170**, **175** is visible in FIG. **1**, showing conductors **170**, **175** extending away from the Schottky diode **147** and over respective ones of the slots **140**, **145**, and forming respective tuning capacitors **180**, **185** adjacent respective slots **140**, **145**. The dielectric of the tuning capacitors **180**, **185** is the silicon dioxide layer forming the insulating mesas **160**, **165**. The conductors **170**, **175** are terminated in respective pads **190**, **195** that are the external connectors of the integrated circuit **100** and supply D.C. electrical power to a component connected across the pads **190**, **195** such as a microrobot, for example.

The conductors **170**, **175** effectively divide the respective slots **140**, **145** into two halves in the manner of a dipole, forming the slot antenna pattern in the gold layer **200** equivalent to a dipole antenna. The insulating (silicon dioxide) mesas **160**, **165** electrically separate the gold conductors **170**, **175** from the gold film **200** in the manner indicated in FIG. **6**. Moreover, as shown in FIG. **7**, the gold film **200** is terminated away from the GaAs mesa **150** so as to not interfere with the Schottky diode **147** (the conductors **170**, **175** and the insulating layers **160**, **165**, are omitted from the partial view of FIG. **7** for the sake of clarity).

The pair of capacitors **180**, **185** shown in FIG. **1** are sized to provide an optimum antenna impedance match. The quarter wavelength thick resonant cavity **135** in combination with the pair of dipole slots **140**, **145** form a highly directional beam antenna whose characteristics (e.g., gain, resonance, etc.) are governed by the cavity **135**. A significant advantage of the cavity **135** is that the reactance of nearby structures to which the integrated circuit **100** may be attached (such as various microrobots or bioengineering devices) do not affect antenna performance. Therefore, the integrated circuit **100** may be mounted on any device to which D.C. electrical power is to be supplied. One advantage of the selected submillimeter wave frequency (about 2500 GHz) is that radiation emanating at that frequency from a remote source toward the integrated circuit **100** is capable of penetrating various materials such as plastic, skin or flesh and the like. Thus, the integrated circuit and the microdevice to which it is attached may be buried under a layer of material or under the skin (for bioengineering applications). Another advantage that will be explored in greater detail below is that the antenna has a nearly purely resistive impedance that matches the impedance of the Schottky diode at this frequency. Also, since the selected frequency is clearly below optical frequencies, a RF antenna such as the one disclosed herein may be employed rather than an optically responsive diode. The advantage is that the antenna may be tuned (by selecting the tuning capacitors **180**, **185**) across a range of frequencies whereas an optical detecting diode must be designed with a bandgap matching the radiation frequency and therefore cannot be readily tuned.

FIG. **8** is a block diagram of the integrated circuit **100** connected to supply D.C. electrical power to a load **800** such as a microrobot. The dipole antenna **805** consists of the pair of slot dipole antennas **140**, **145** and the resonant cavity **135** of FIG. **1**. The diode **810** is the diode **147** of FIG. **1**. The filter **820** is the pair of filter capacitors **180**, **185** of FIG. **1**. The connecting pad **830** is the pair of conductive pads **190**, **195** of FIG. **1**.

FIG. **9** illustrates one plane of the 3-dimensional spatial distribution of the gain of the slot antenna structure **135**, **140**, **145** of FIG. **4**. The relative gain is plotted as the length of a vector extending from the origin to the curve as a function of angle of incidence A. The plot of FIG. **9** shows that there is a very large forward-to-back gain ratio (in excess of 6 dB or more) and a narrow beam width in the forward direction (65 degrees at 3 dB). The narrow beam width is confirmed by the plots of E-field and H-field attenuation as a function of the angle A of FIGS. **10** and **11** respectively.

FIG. **12** is a Smith chart of the impedance of the slot antenna structure **135**, **140**, **145** FIG. **4** for impedances

normalized to 50 Ohms. FIG. **12** indicates that at a frequency of 2445 GHz the impedance is almost purely resistive at a normalize value of 0.32, which is 16 Ohms. This is the impedance of the Schottky diode **147** at 2445 GHz, so that a nearly perfect impedance match is provided for optimum power transfer efficiency.

FIG. **13** illustrates the integrated circuit **100** mounted on a microrobot **400** with 2445 GHz radiation (from a laser for example) illuminating the integrated circuit **100**.

FIG. **14** illustrates how the pair of dipole slot antennas **140, 145** may be replaced by an equivalent pair of conductor dipole antennas **310, 315**. The gold film **200** covering the exposed top of the membrane **125** is eliminated and the dipole antennas are formed integrally with the gold conductors **170, 175** in the pattern illustrated in FIG. **14**. The length of each dipole antenna **310, 315** is one half wavelength. Each dipole antenna **310, 315** is divided into two sections (**310***a*, **310***b* and **315***a*, **315***b*), the diode **147** being connected across the two sections of each dipole **310, 315**. The center-to-center spacing between the two dipole antennas **310, 315** is a half wavelength. A pair of tuning capacitors **330, 340** connected to opposite sides of the diode **147** may be formed in the gold conductor pattern as shown in FIG. **14**.

FIG. **15** illustrates how a full wave rectifier bridge of four matched Schottky diodes **610, 620, 630, 640** may replace the single Schottky diode **147** of FIG. **1**. In FIG. **15**, the conductors **170, 175** each extend only from the far side of a respective slot **145, 140** to a corresponding terminal pair of the rectifier bridge, while a pair of output conductor **650, 660** extend from the remaining terminal pair of the rectifier bridge to output pads **670, 680**.

While the antenna length of the preferred embodiment is a half wavelength, other suitable lengths may be employed such as multiples of ⅛ (e.g., ⅝ wavelength). Moreover, while the cavity length and width have been described as being preferably about one wavelength, they may be multiples of one wavelength. Moreover, the cavity thickness, while having been described as being preferably one quarter wavelength, may be odd multiples of one quarter wavelength. However, it should be noted that it is felt the performance described herein is expected to be most readily attained in the preferred embodiment.

While the invention has been described in detail with reference to preferred embodiments, it is understood that variations and modifications thereof may be made without departing from the true spirit and scope of the invention.

What is claimed is:

1. A submillimeter wave antenna and rectifier integrated circuit for mounting on and supplying D.C. electrical power to a microminiature device, said integrated circuit comprising:

an underlying cavity of semiconductor material having a length and width corresponding to a selected submillimeter wavelength and a thickness corresponding to one quarter of said selected wavelength, said cavity having side walls and a planar conductive floor;

a planar membrane of semiconductive material constituting a ceiling of said cavity and being parallel to said planar floor;

an antenna structure on said planar membrane, said antenna structure comprising antenna elements each having a length corresponding to a predetermined fraction of said selected submillimeter wavelength;

a semiconductor rectifier formed on said membrane and connected across said antenna structure.

2. The integrated circuit of claim **1** wherein said antenna structure comprises plural parallel spaced apart dipole antennas each of a length of half of said selected wavelength and each separated into two sections.

3. The integrated circuit of claim **2** wherein said dipole antennas comprise two elongate slot antennas and said rectifier is connected between said two elongate slot antennas comprising respective slots formed through said membrane.

4. The integrated circuit of claim **2** wherein said dipole antennas comprise two conductor antennas and said rectifier is connected between the two sections of each of said dipole antennas.

5. The integrated circuit of claim **3** further comprising a pair of conductors formed as a conductive thin film layer overlying said membrane and connected to opposite sides of said rectifier, each of said pair of conductors having a respective elongate portion extending transversely across a respective one of said elongate slots whereby to divide the one slot into two equal slot sections to define corresponding dipole elements.

6. The integrated circuit of claim **5** wherein said rectifier comprises a diode.

7. The integrated circuit of claim **6** wherein said rectifier comprises a one half or full-wave rectifying diode bridge.

8. The integrated circuit of claim **6** wherein said diode comprises a GaAs layer on said membrane and a pair of contacts an a top surface of said GaAs layer to respective ones of said pair of conductors.

9. The integrated circuit of claim **1** wherein said conductive floor comprises a metallic planar film having an array of voids formed therethrough, each of said voids having an area sufficiently large to permit liquid etchant flow therethrough and sufficiently small to have negligible effect at said selected wavelength.

10. The integrated circuit of claim **9** further comprising an etch stop layer between a base layer and said membrane.

11. The integrated circuit of claim **5** further comprising a conductive cover layer overlying portions of said membrane not covered by said pair of conductors, said conductive cover layer being electrically separate from said pair of conductors, said elongate slots forming corresponding voids in said conductive cover layer.

12. The integrated circuit of claim **1** wherein said selected submillimeter wavelength is about 120 microns.

13. The integrated circuit of claim **12** wherein said rectifier comprises a Schottky diode mesa structure of less than about ten microns in length and width.

14. The integrated circuit of claim **1** wherein said rectifier comprises a Schottky diode mesa structure and said selected wavelength corresponds to a frequency at which said antenna structure has an impedance at least nearly matching an impedance of said Schottky diode at the same frequency.

15. The integrated circuit of claim **5** further comprising an insulating thin film layer between conductor thin film layer and said membrane and a pair of capacitors connected to respective ones of said pair of conductors formed in said conductive thin film layer and separated from said membrane by said insulating thin film layer.

16. The integrated circuit of claim **15** wherein said pair of capacitors comprise tuning capacitors.

17. The integrated circuit of claim **1** wherein the semiconductor material of a base layer and the semiconductor material of said membrane are each intrinsic semiconductor material.

18. The integrated circuit of claim **17** wherein said rectifier comprises doped semiconductor material comprising a lower n+ layer of GaAs and an upper n layer of GaAs and a pair of metal contacts on a top surface of said n layer constituting opposite terminals of said rectifier.

19. A submillimeter wave antenna and rectifier integrated circuit for mounting on and supplying D.C. electrical power to a microminiature device, said integrated circuit comprising:

an underlying cavity of semiconductor material having a length and width lying in a plane and corresponding to a selected submillimeter wavelength and having a thickness normal to said plane, said cavity having side walls and a planar conductive floor parallel to said plane;

a planar membrane of semiconductive material constituting a ceiling of said cavity and being parallel to said planar floor;

an antenna structure on said planar membrane, said antenna structure comprising antenna elements each having a length corresponding to a predetermined fraction of said selected submillimeter wavelength, said thickness of said cavity being related to said selected submillimeter wavelength in such a manner that said cavity produces in said antenna structure a front-to-back antenna gain ratio in a direction normal to said plane of at least 6 dB;

a semiconductor rectifier formed on said membrane and connected across said antenna structure.

20. The integrated circuit of claim **19** wherein said antenna structure comprises plural parallel spaced apart dipole antennas each of a length of half of said selected wavelength and each separated into two sections.

21. The integrated circuit of claim **20** wherein said dipole antennas comprise two elongate slot antennas and said rectifier is connected between said two elongate slot antennas comprising respective slots formed through said membrane.

22. The integrated circuit of claim **20** wherein said dipole antennas comprise two conductor antennas and said rectifier is connected between the two sections of each of said dipole antennas.

23. The integrated circuit of claim **21** further comprising a pair of conductors formed as a conductive thin film layer overlying said membrane and connected to opposite sides of said rectifier, each of said pair of conductors having a respective elongate portion extending transversely across a respective one of said elongate slots whereby to divide the one slot into two equal slot sections to define corresponding dipole elements.

24. The integrated circuit of claim **23** wherein said rectifier comprises a diode.

25. The integrated circuit of claim **24** wherein said rectifier comprises a full-wave rectifying diode bridge.

26. The integrated circuit of claim **24** wherein said diode comprises a GaAs layer on said membrane and a pair of contacts on a top surface of said GaAs layer to respective ones of said pair of conductors.

27. The integrated circuit of claim **19** wherein said conductive floor comprises a metallic planar film having an array of voids formed therethrough, each of said voids having an area sufficiently large to permit liquid etchant flow therethrough and sufficiently small to have negligible effect at said selected wavelength.

28. The integrated circuit of claim **27** further comprising an etch stop layer between a base layer and said membrane.

29. The integrated circuit of claim **23** further comprising a conductive cover layer overlying portions of said membrane not covered by said pair of conductors, said conductive cover layer being electrically separate from said pair of conductors, said elongate slot forming corresponding voids in said conductive cover layer.

30. The integrated circuit of claim **19** wherein said selected submillimeter wavelength is about 120 microns.

31. The integrated circuit of claim **30** wherein said rectifier comprises a Schottky diode mesa structure of less than about ten microns in length and width.

32. The integrated circuit of claim **19** wherein said rectifier comprises a Schottky diode mesa structure and said selected wavelength corresponds to a frequency at which said antenna structure has an impedance at least nearly matching an impedance of said Schottky diode at the same frequency.

33. The integrated circuit of claim **23** further comprising an insulating thin film layer between conductor thin film layer and said membrane and a pair of capacitors connected to respective ones of said pair of conductors formed in said conductive thin film layer and separated from said membrane by said insulating thin film layer.

34. The integrated circuit of claim **33** wherein said pair of capacitors comprise tuning capacitors.

35. The integrated circuit of claim **19** wherein the semiconductor material of a base layer and the semiconductor material of said membrane are each intrinsic semiconductor material.

36. The integrated circuit of claim **35** wherein said rectifier comprises doped semiconductor material comprising a lower n+ layer of GaAs and an upper n layer of GaAs and a pair of metal contacts on a top surface of said n layer constituting opposite terminals of said rectifier.

37. The integrated circuit of claim **19** wherein said antenna structure has a 3 dB beamwidth of about 65 degrees.

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